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Structural health monitoring of bolt pre-load looseness using smart-washers based active sensing approach

* DongdongChen[1], Linsheng Huo[2] and Gangbing Song[3]

[1], [2] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, Liaoning 116024, China
[3] Smart Materials and Structures Laboratory, Department of Mechanical Engineering, University of Houston, Houston, TX 77204, USA
[1] chendongdlut@mail.dlut.edu.cn

ABSTRACT

Bolted connection, as one of the most common connection forms to make two or more parts/components work together in engineering structures, its safety is very important to ensure the health of the whole structure. However, bolted loosening or pre-load degradation may induce the failure of the bolt connection, which will threaten the normal operation of the structure system, so it will benefit if the health condition of the bolt connection can be monitored in real time. In this paper, “smart washer”, fabricated by embedding a piezoceramic patch into two pre-machined flat metal rings, was invented and first introduced as a transducer to detect the looseness of a bolted connection. A simple specimen, which consists two steel plate connected by a pair of bolt and nut and two smart washers, was fabricated as the test object to study the performance of the “smart-washers” (SWs). For the specimen, a smart washer was used as an actuator to generate stress wave, and the other one was used as a sensor to detect the propagated wave that traveled through the interface of the bolted connection. Time reversal method was employed to quantify the energy of the stress wave propagated between two washers, thus a relationship can be built between the extents of pre-load degradation of the bolt connection and the response signal of the stress wave traveled between two washers. In addition, a normalized bolt looseness index was proposed to evaluate the looseness of a bolt connection based on the wavelet energy analysis.

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[1] Ph.D candidate
[2] Associate Professor
[3] Professor

1. INTRODUCTION

Bolted connection is one of jointed ways in civil and mechanical engineering. Compared with other kinds of connections, bolted connection has many advantages, including simple connection and easy dismantle, less material consumption, less project execution time, and better connection behavior. It has gained great popularity in steel components and structures due to these advantages.

Research have been conducted to try to measure or monitor the pre-load looseness of bolt connection. Argatov et al (Argatov et al. 2010) proposed a simple formula based on electrical constriction resistance of the rough contact interface to monitor the structure health of bolted joints. Johnson et al (Johnson et al. 1986) used ultrasonic technique and time-of-flight measurements to calculate the stress acting on the bolt. Amerini and Meo (Amerini et al. 2011) developed a tightening/loosening state index based on the first-order acoustic moment. Joshi et al (Joshi et al. 1984) used the pseudo-continuous-wave technique to detect the mechanical resonance frequency shift of bolt stress. The piezoelectric impedance method also shows potential effectiveness to estimate the civil structure component (Rutherford et al. 2007; Sohn et al. 2003). Gyuhae Park et al (Cudney et al. 2000) presented experimental evidences of structural point impedance changes in several damaged civil structural components. Ritdumrongkul et al (Fujino et al. 2006) used the mechanical impedance to identify the location and the extent of damage in a two-joint and a four-joint aluminum beam structures. An and Sohn (An et al. 2012) developed an integrated bolt loosening detection method utilizing impedance and guided wave. Wait et al (Wait et al. 2005) combined impedance methods and Lamb wave propagations to detect and locate the damage.

In this paper, a new device, called “smart washer” was invented to identify the loss of bolt pre-load by combining piezoceramic transducers with the active sensing approach. The smart washer is fabricated by embedding a piezoceramic patch into two pre-machined flat metal rings. Time reversal method was used to improve the Signal to Noise Ratio (SNR). Besides, a time domain analysis and a wavelet packet-based analysis method were applied in the data processing. A wavelet packet-based bolt load loss index was developed to quantify the load loss of the bolted connection specimen.

2. PRINCIPLES AND METHODS

2.1 Smart washer

Piezoceramic is one kind of energy conversion materials which has direct piezoelectric effect and converse piezoelectric effect, as show in Fig. 1. The direct piezoelectric effect can convert stress or strain energy into electric energy, and the converse piezoelectric effect means the reverse transformation. Lead Zirconate Titanate (PZT) is used as piezoelectric material. Different PZT modes, such as d_{33}, d_{31} or d_{15} modes, can be selected according to the detection objective. In this paper, the PZT with d_{33} mode which shown as Fig. 2 was applied in the experiments due that it is suitable for the detection of bolt pre-load looseness.

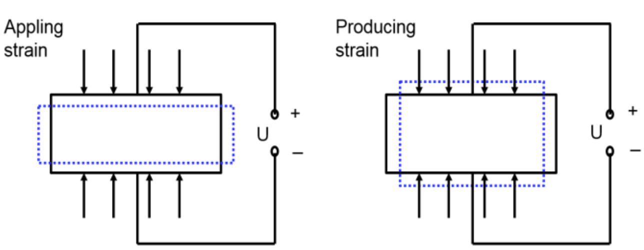


Fig. 1 Direct piezoelectric effect and converse piezoelectric effect

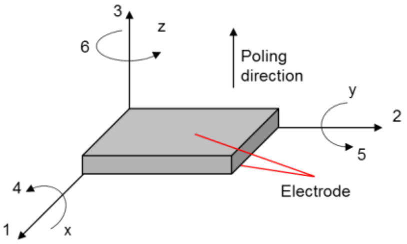


Fig. 2 The poling of PZT sensor in 3-direction

The proposed smart washer (SW) is a new kind of sensor which sandwiched the processed PZT in the washer (Huo et al. 2017), as shown in Fig. 3 and Fig. 4. The smart washer is convenient in mounting bolts and sensitive to the bolt load looseness. With the help of signal generator and oscilloscope, the signals obtained from the smart washer (SW) can reveal the bolt load loss clearly.

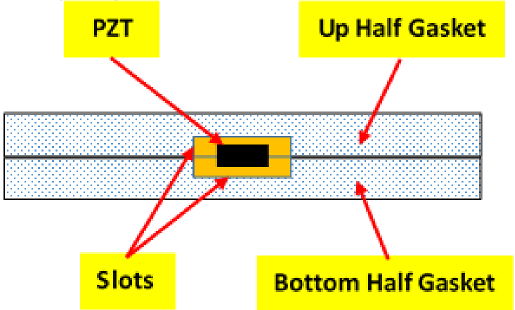


Fig. 3 The design of smart washer

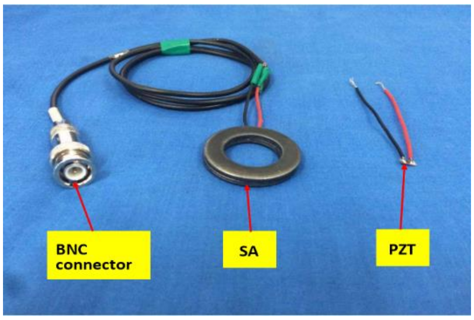


Fig. 4 Fabricated smart washer with a connecting BNC cable

2.2 Wavelet Energy Based Bolt Pre-Load Looseness Index

The interface contact between the two steel plates connected by the bolt will affect the propagation of the stress wave. The pre-load on the bolt can significantly influence the wave propagation, and the attenuation of the stress wave can be detected by using wavelet analysis. Han et al (Han et al. 2005) used wavelet packet-based method to identify the damage of the beam structures and proposed wavelet packet energy rate index (WPERI) as the damage detection feature to evaluate the damage extent of beam structures.

The *n*-level wavelet is applied to decompose the received signals, as shown in Fig. 5, and the decomposed signal will be used to detect the bolt looseness.

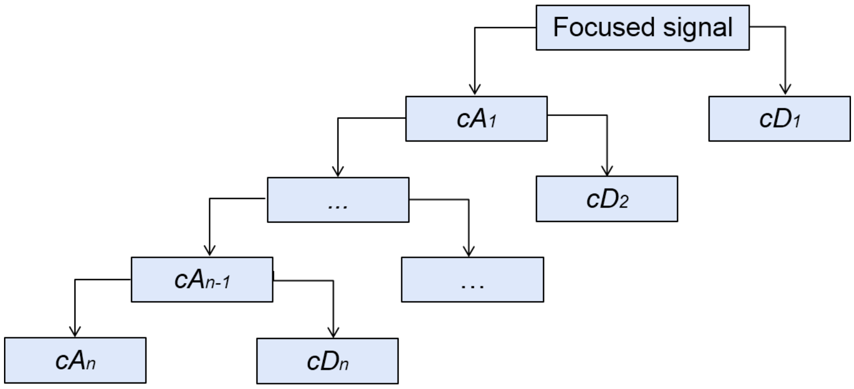


Fig. 5 The scheme of n-level wavelet decomposition

In Fig. 5, the original signal is decomposed to n+1 coefficient signal sets $\{cD_1\}, \ldots, \{cD_n\},\{cA_n\}$. $\{cD_1\}$ is the highest frequency coefficient set and $\{cA_n\}$ is the lowest one. In order to define the wavelet energy ratio, sets $\{cD_1\},\{cD_2\} \ldots ,\{cD_n\},\{cA_n\}$ are renamed as $\{S_1\},\{S_2\}, \ldots , \{S_n\},\{S_{n+1}\}$. The samples of each set $\{S_1\},\{S_2\}, \ldots ,\{S_n\},\{S_{n+1}\}$ can be expressed as X_{ij}, and X_{ij} is shown as follow:

$$X_{ij}=[X_{i1}, X_{i2}, X_{i3},\ldots, X_{im}]$$

where i=1,2,…,n+1, j=1,2,…,m and m is the number of samples in each set, and the energy of each set in $\{S_1\},\{S_2\}, \ldots ,\{S_n\},\{S_{n+1}\}$ can be calculated by Eq.(1).

$$E_i^l = \sum_{j=1}^{m} \left| X_{ij} \right|^2 \tag{1}$$

where l=1,2,…,p, p is the sequence number of experiments, and E_i^l is the energy of i^{th} set at l^{th} experiment. Therefore, wavelet energy ratio for each discomposed coefficient set can be obtained.

$$W_i^l = \frac{E_i^l}{\sum_{i=1}^{n+1} E_i^l} \tag{2}$$

where W_i^l denotes the i^{th} set wavelet energy ratio of l^{th} experiment. According to the change of the ratio, the bolt pre-load loss will be identified.

In order to quantify the change of pre-load loss degree, the normalization of wavelet energy ratio of W_i^l is proposed:

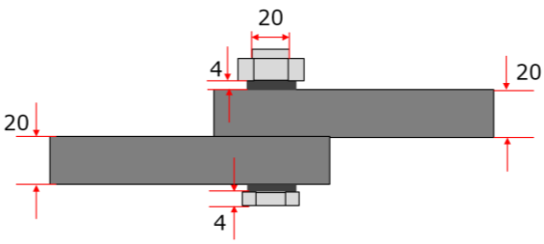
$$I_i^l = \frac{W_i^b - W_i^l}{W_i^b - W_i^t} \tag{3}$$

where I_i^l represents the pre-load loss index or bolt looseness index of i^{th} set at l^{th} experimental condition, W_i^b is the i^{th} set wavelet energy ratio without bolt looseness, which was regarded as baseline energy ratio, W_i^t is i^{th} set energy ratio for the bolt with completely looseness case.

With the looseness develop, the corresponding bolt looseness index for each set of wavelet energy ratio will change, and it can reflect the looseness degree of bolt.

3. EXPERIMENTAL SETUP

The specimen included two steel plates, which were connected by a bolt and a nut. Two smart washers (SWs) were mounted at each side of the specimen, the detailed dimension of the specimen and the locations of the smart washers were shown in Fig. 6.



(a) Dimension of the bolt connection (Unit: mm)


(b) The bolt assembly

Fig. 6 Detailed dimension of the specimen and installation

In this study, data acquisition devices (NI - USB 6366) was used to generate and receive the signals. The power amplifier was employed to amplify the emitted signal. The torque of the bolt was measured by the torque wrenches, as shown in Fig. 7, and the instruments used in the experiment is shown in Fig. 8.

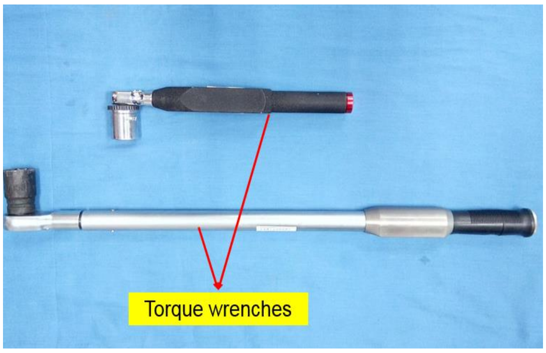


Fig. 7 Torque wrench

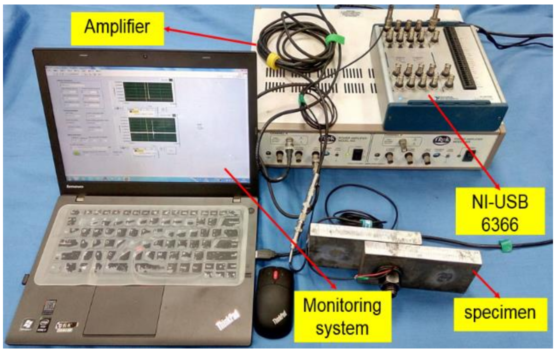


Fig. 8 Instruments of the experimental setup of the smart washers to detection

4. WAVELET ENERGY-BASED INDEX ANALYSIS

A time domain analysis and a wavelet packet-based energy analysis method were applied to process the received signal. The experimental sequence number and the pre-load information are shown in Table 1. Fig. 9 shows the received signals with 167.5N•m applied torque. The received signal with different torques were plotted in Fig. 10.

Table 1 Experimental sequence number and pre-load information of eleven cases

Sequence number	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th

Pre-load (N·m)	205	182.5	167.5	142	127.5	104.5	80.2	63.7	42.3	21.2	0

Four-level wavelet was used to decompose the eleven received signals, which was considered enough to provide accurate results. Eleven pre-load cases of low-frequency wavelet energy ratio in 5th set (W_5^1, W_5^2, W_5^3 ,…, W_5^{11}) can be obtained with the equation (1) and (2). By substituting them into equation (3), the bolt pre-load looseness index can be obtained. Fig.11 shows the bolt pre-load looseness index of eleven pre-load cases in the 5th set.

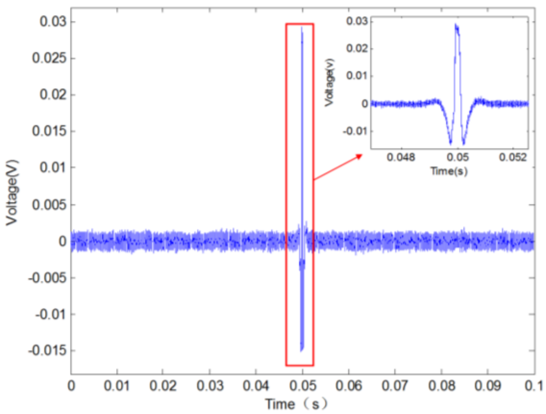


Fig. 9 The received signals with 167.5N•m applied torque

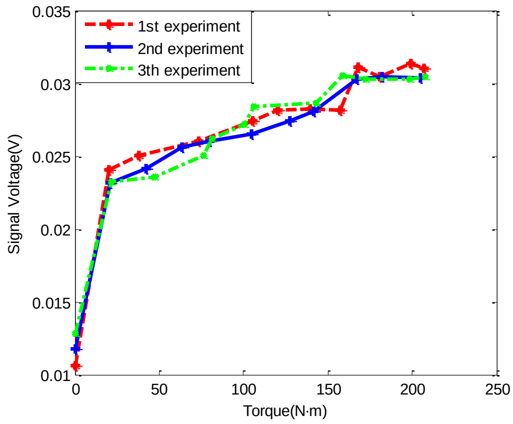


Fig. 10 Peak values of the eleven bolt pre-load conditions

As shown in Fig. 10, the voltage of the received signal decreased with the decrease of bolt pre-load. Therefore, the bolt pre-load loss can be identified using the received peak value based on the relationship shown in Fig. 10. The relationships between the peak value of the received signal and bolt pre-load are related with positive exponent. It should be noted that when the torque reached 180N·m, the peak value of received signal almost reach saturation with received peak around 0.031V, which indicates that the further increase of the pre-load on the bolted connection will have little impact on the contact area between the two plates, and therefore almost no impact on the wave propagation through the interfaces.

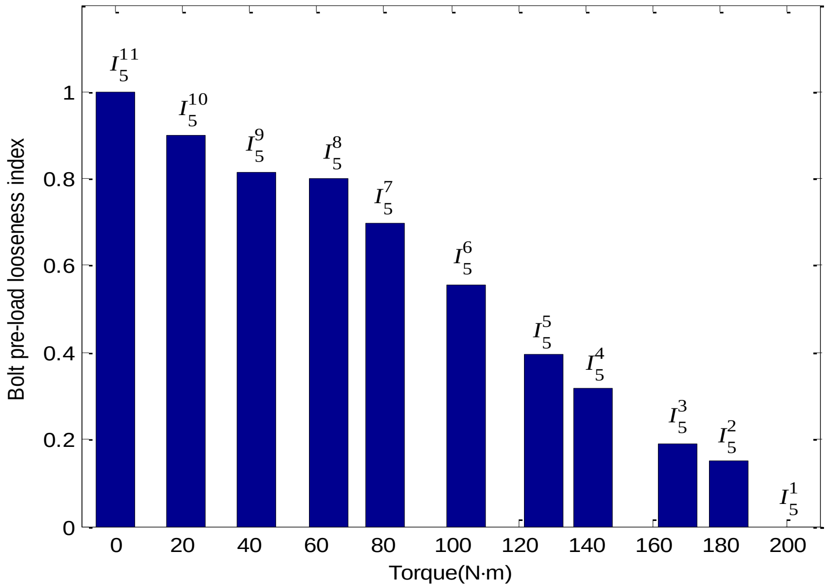


Fig.11 Peak values of the eleven bolt pre-load conditions

The relationship between bolt looseness index and applied torque is shown in Fig. 11. The bolt looseness index I_5^1 for the case of bolt load at 205 N·m (without looseness) is 0 according to the definition beforehand. While for the case of bolt load at 0 N·m (completely looseness), the bolt looseness index I_5^1 is 1. It is clear from the Figure that the bolt looseness index increases with the reduction of the applied torque. It can be concluded that the bolt looseness index can reflect the severity of the bolt looseness effectively.

5. CONCLUSIONS

In this paper, a piezoceramic based smart washer is proposed to monitor the pre-load loss of a bolted connection. The smart washer which offers protection to the embedded piezoceramic transducers is robust and easy to use. The experimental result proved that it is a reliable approach for bolt pre-load looseness detection. The peak values of the received signals are attenuated with the bolt load losing in time domain analysis. According to the change of the peak values, the trend of bolted load loss can be obtained. Furthermore, a wavelet energy ratio based bolt pre-load looseness index using the active sensing technique from the smart washers also reflects the bolt pre-load looseness.

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